Evaluation of ATD Models for Simulating Occupant Responses under Vertical Impact

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Abstract

Numerical anthropomorphic test devices (ATD) have been developed for the main purpose of simulating vehicle frontal crash events. These ATD models are increasingly employed for military vehicle occupant impact simulations following the detonation of roadside bombs, landmines or Improvised Explosive Devices (IED). In this paper, the authors compared simulated and experimental predictions for thoraco-lumbar spine injury based on pelvis acceleration, dynamic response index, and lumbar axial force. It was found that none of the numerical ATD models investigated could generate accurate enough responses, when compared to the experimental tests with the physical ATD model. It is thus concluded that further enhancements to the numerical ATD models investigated are required for simulating military vehicle occupant responses under vertical impact loading.

Introduction

In addition to the traditional threats to vehicle occupants from frontal crash and side impact, passengers of military vehicles can also be subjected to vertical shock loading on their thoraco-lumbar spine and legs arising from the detonation of roadside bombs, landmines or Improvised Explosive Devices (IED). In such explosion events, the vehicle hull is subjected to high level transient momentum loading, resulting in an acceleration impulse that transfers to the occupant through the vehicle floor and the seat.

When conducting experimental blast testing, full-scale anthropomorphic test devices (ATD) are used to evaluate the survivability potential of passengers. Equivalent investigations involving ATD models are also conducted numerically. However, existing ATD numerical models have been developed mainly for frontal crash or side impact simulations, and have not been validated against vertical impact loading experienced by military vehicle occupants. Polanco and Littell (2011) performed studies on ATD responses using Hybrid II and Hybrid III 50th percentile mannequins in a typical vertical impact loading condition for an occupant sitting in a seat platform. They found dramatic differences in their pelvis acceleration and lumbar force responses due to different lumbar structures in these two mannequin models. They also checked the validity of the LSTC Hybrid III and the FTSS Hybrid III models, and concluded that the FTSS model achieved better correlation than the LSTC model with test data [1]. In this paper, the authors re-visit this topic by simplifying the test setup and removing as many potential influential factors as possible. With a focus on the latest Hybrid III physical ATD model and 3 numerical ATD models of different level of complexity, the validity of these ATD numerical models is then assessed with confidence.

The following sections present drop test results of a Hybrid III 50th percentile male ATD. Numerical simulations were also conducted to simulate the test setup. Comparisons of pelvis acceleration, DRI, and lumbar force were then made to analyze the applicability of these numerical ATD models. To extend observations from the above comparisons to more practical loading scenarios, blast off test simulations were also conducted and the results were compared with the signals recorded in an experimental blast off test.

Experiments – Test Setup

As a baseline, a simple drop test was experimentally conducted with a 50th percentile male ATD sitting on a rigid platform, to simulate the vertical impact from a blast. Through the use of this test setup, uncertainties arising from complicated seat and test fixture structures were avoided. During the test, the assembly consisting of the ATD and a platform was placed in a controlled drop tower facility to generate an impact pulse on the ATD. The pelvis acceleration and lower lumbar force were recorded.

In general, the ATD response depends on the type of mannequin (weight/size and model structure), the seat (shock attenuation mechanism, seat structure, cushion, and footrest), and the loading characteristics. There exist various mannequin types, including the Hybrid II, the Hybrid III, and the Thor. For each type, there are different sizes, such as the 5th female, 50th male and 95th male models with different weights and heights. Even for the Hybrid III 50th mannequin, there exist two sub-types: the standard (seated) and the pedestrian (standing) models, which differ in terms of pelvis and lumbar designs. For this study, the Hybrid III 50th percentile male of the seated variant was employed. Its basic weight is 78 kg (171 lbs). The mannequin was instrumented to record the pelvis accelerations and lumbar loads for injury assessment.

There exists an even wider variety of blast mitigation seat designs. In order to avoid uncertainties introduced by a seat, the mannequin was placed directly on the top surface of a carriage table as shown in Figure 1. Med-Eng's drop-tower testing facility was used for the test, which includes a carriage table that can be lifted up to a desired height and then released, simulating the vehicle platform. The carriage table was well guided and could only move in the vertical direction. After a period of free fall, the carriage table hits a layer of elastomeric material located on the ground. This material acts as a pulse shaper to generate the desired acceleration pulse mimicking the pulse a vehicle would experience under blast.

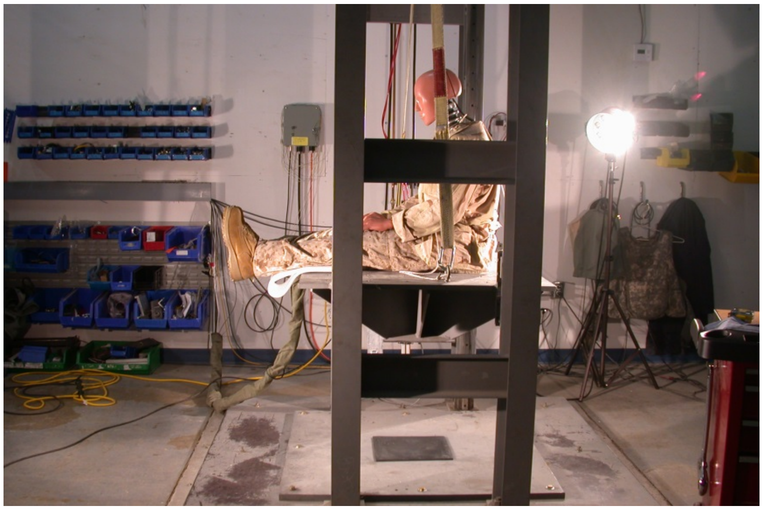

Figure 1: Med-Eng's drop-tower testing facility

Simulations

Simulations of the experimental platform test were then performed with LS-DYNA® using different numerical ATD models. The three ATD models used for this study are listed in Table 1. There are many differences among these ATD models, including element size, modeling strategy, etc. Table 1 lists the number of elements and the number of nodes for each of these ATD models. These numbers are usually used to assess the complexity of the model. Based on the number of elements and number of nodes, it can be claimed that the higher the ATD model ID, the more details of the ATD structure were modeled, and consequently the more CPU time is needed for computing.

Table 1: Numerical Hybrid III models used for this study

ATD ID	**Developer**	**Model Version**	**Number of Elements**	**Number of Nodes**
I	Livermore Software technology Corporation (LSTC)	LSTC H3 50^{TH} FAST 120702 V2.0	4278	7402
II	First Technology Safety Systems (FTSS)	H350 s3 v7.1.8	130514	100323
III	National Crash Analysis Center (NCAC) at The George Washington University's Virginia Campus	NCAC H3 50^{TH} 130528 BETA	452347	292233

A numerical model is meant to represent the actual test setup as much as possible. In addition to the ATD model, the drop tower carriage table was modeled with rigid material and constraints were applied to guide the table to move only in the vertical direction. Figure 2 shows the resulting drop-tower carriage numerical model with an ATD III sitting on it. A keyword card *BOUNDARY_PRESCRIBED_MOTION_RIGID_ID [2] was used to apply the impact pulse in terms of actual velocity time history, which was derived by integrating an acceleration signal that was recorded through an accelerometer mounted on the center of the table during the drop tests. Proceeding this way, the loading on the table was precisely modeled. For this test, a change of velocity of 4.38 m/s with a corresponding acceleration pulse duration of 8 ms was chosen.

The contact between the ATD and the top surface of the table was defined using a keyword card *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. Gravity was applied to the whole model through *LOAD_BODY_Z. The pre-stress caused by the gravity was purposely not included in the model as the simulation is started a few milliseconds before the bottom of the carriage table hits the pulse shaper on the ground. At this starting point, the ATD has been through a period of free fall. In this free fall period, all the compression generated by the gravity before the release of the whole assembly was decompressed, resulting in no or less gravity-related pre-stress in the ATD.

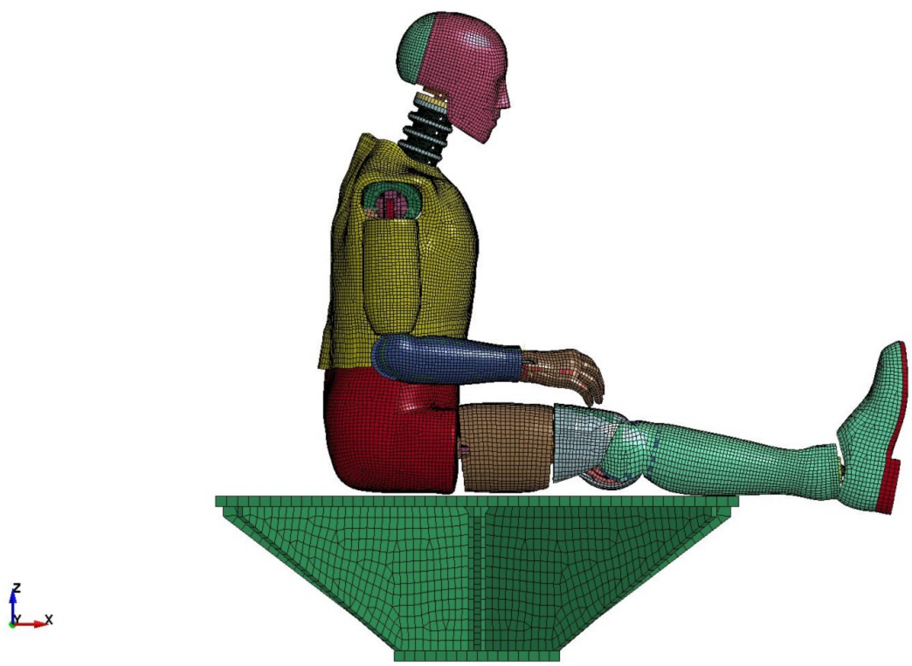

Figure 2: Numerical model with ATD III

Comparisons

The most relevant injury criteria in this study are related to the measurements of pelvis acceleration and lumbar force. Pelvis acceleration is the required input for the Dynamic Response Index (DRI) model that has been widely used to assess the probability of thoraco-lumbar spine injury [3]. The DRI model is a mass-spring-damper system, as presented in Figure 3.

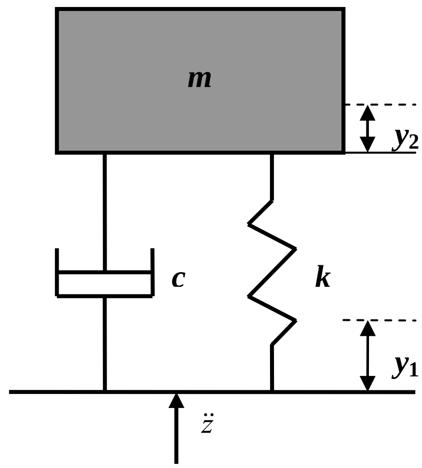

Figure 3: Mathematical model for the spine used for the application of the DRI injury criterion

m, *k*, and *c* are physical parameters of mass, spring rate, and damping coefficient, respectively. The equation of motion for this single mass-spring-damper system is:

$$\ddot{\delta}(t) + 2\zeta\omega_n\dot{\delta}(t) + \omega_n^2\delta(t) = \ddot{Z}(t) \tag{1}$$

where $\delta = y_1 - y_2 (> 0)$ is the relative displacement (compressive) of the system, $\zeta = c/2m\omega_n$ the damping coefficient ratio, $\omega_n = \sqrt{k/m}$ the natural frequency, and $\ddot{Z}(t)$ the pelvis acceleration in its local vertical direction. The DRI for the cranial direction (Z-axis) is calculated by the maximum relative displacement δ_{max}, ω_n and the gravity acceleration *g*.

$$DRI = \frac{\omega_n^2\delta_{\max}}{g} \tag{2}$$

Pelvis acceleration histories from the drop-tower test and simulations with the three different ATD models are presented in Figure 4. The experimental drop-tower and simulated pelvis acceleration using the ATD model I were filtered through a CFC1000 digital filter. Simulated signals using ATD models II and III contain little noise and the application of CFC1000 digital filter has little effects on them. It is observed that both signal shape and peak value of the pelvis acceleration curve from the ATD Model I simulation are significantly different from the experimental test results. The simulation using ATD model III generated a pelvis acceleration curve that is closer in shape to the experimental test result, but its peak value of 740 g is much higher than the experimental value of 502 g. The simulation using ATD model II generated a peak value of 224 g, approximately half of the experimental result. ATD Model II's acceleration shape is closer to the experimental one than that of ATD I, but not as close as that of ATD III.

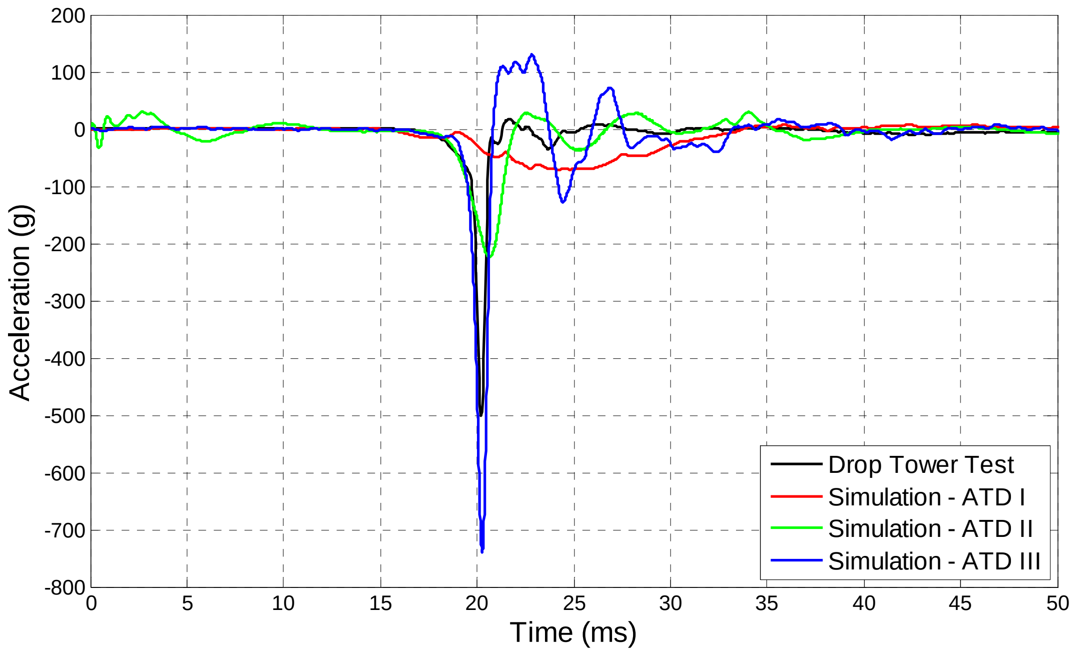

Figure 4: Comparison of pelvis accelerations

Using the pelvis acceleration histories as input to the DRI model, DRI curves were computed and presented in Figure 5. Once again, the peak DRI value generated by ATD I is found to significantly deviate from the experimental one, while values for ATD II and ATD III are close, with ATD II being the closest one.

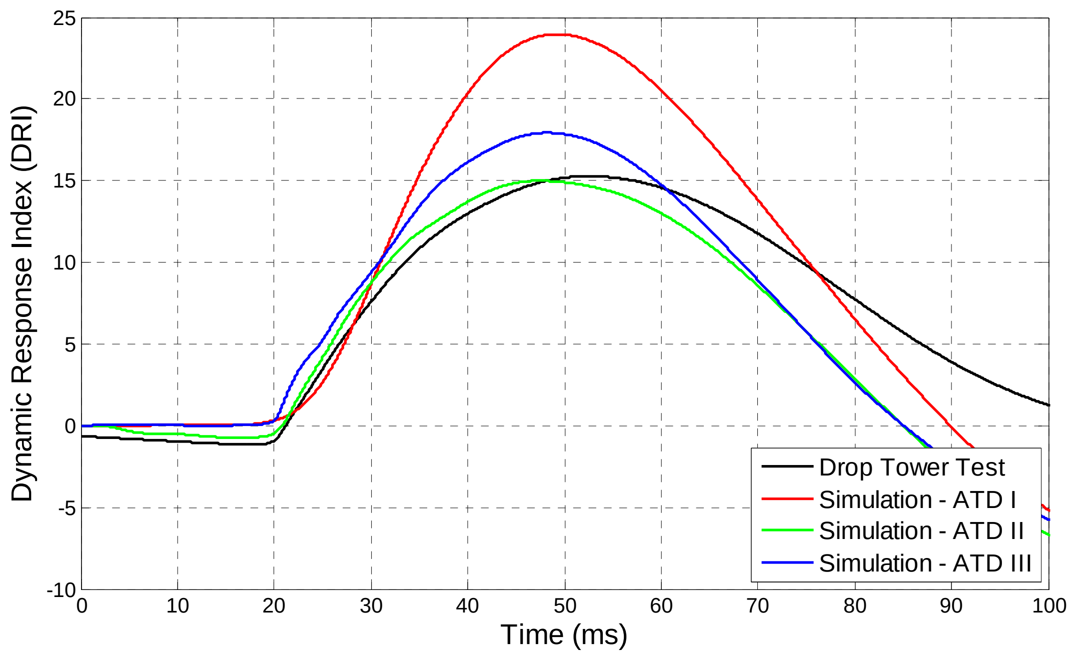

Figure 5: Comparison of DRI histories

Although the DRI is a widely used injury criterion for thoraco-lumbar spine injury, the axial lumbar force is also considered a useful parameter of relevance to spine injury. Figure 6 shows the experimental and simulated lumbar time histories. All simulated lumbar force peak values were found to be much higher than the experimental peak force. Furthermore, the shapes of the simulated time histories of the lumbar force are in no way similar to the recorded experimental signal. The only similarity worthy of mention is the rise rate at the onset of loading for ATD III as compared to the experimental curve.

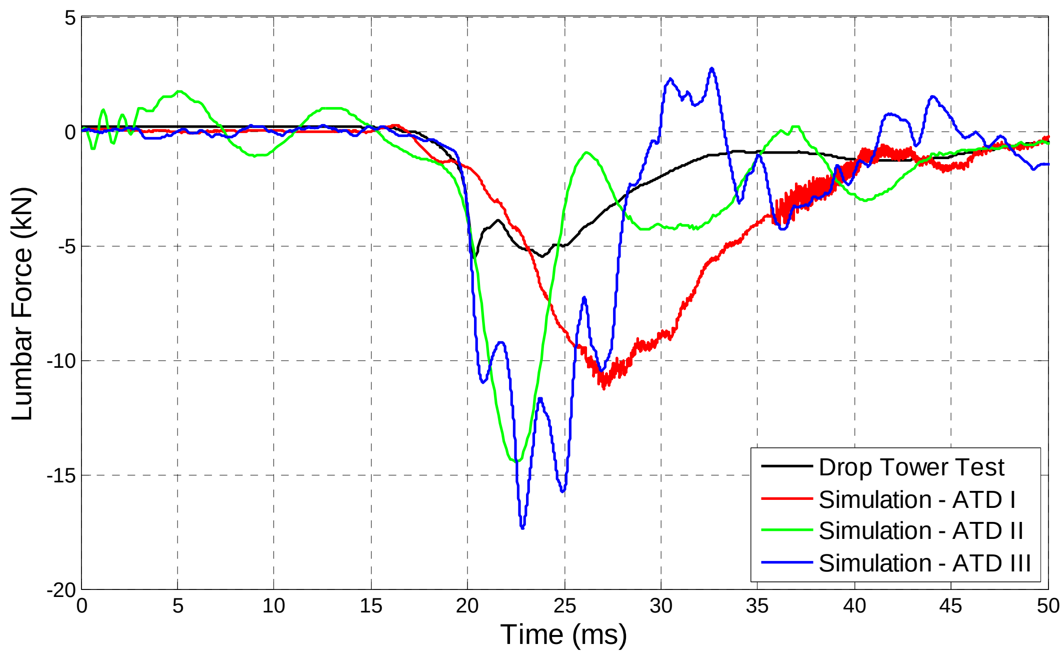

Figure 6: Comparison of axial lumbar forces

The above observations were derived from the harsh impact test conducted involving only an ATD and a rigid carriage table, where the impact pulse on the buttocks of the ATD has a pulse duration of approximately 30 ms and a peak value in excess of 50 kN. Although observations from such harsh loading could be used to draw conclusions on these ATD models, it might not be possible to apply these conclusions towards guiding blast mitigation seat design practices that could dramatically change the nature of the impact loading on its occupant. In the following paragraphs, the applicability of these ATD models is examined through a blast off test involving a Hybrid III 50th percentile male mannequin seated in a Med-Eng blast mitigation seat.

Theoretically, the level of fidelity of a FEA model is closely related to the size of its elements, which limits the highest frequency mode the model can simulate. More specifically, the ability of a given model mesh to simulate the experimental structural response is limited by its highest response frequency, which in turn, is highly dependent on the pulse duration. In other words, the behavior of a model under an impact of short pulse duration may be different from that under an impact of longer pulse duration. It is thus critical to perform the model comparison in a realistic setup in terms of pulse duration.

In most military vehicle scenarios, occupants sit on a blast mitigation seat comprising a well-designed shock attenuation mechanism and a cushion. The shock attenuation mechanism can dramatically reduce the peak value and increase the pulse duration of the impact pulse on the buttocks of the occupant. To evaluate the validity of the ATD models under more realistic and representative pulse loading, a test with a blast mitigation seat was simulated using the same three ATD numerical models. The test was a blast off one with a change of velocity of approximately 6 m/s. Figure 7 shows the model of the complete seating system with ATD I. Due to the lack of detailed information regarding the actual ATD sitting posture and the properties of the footrest, it was difficult to accurately model the experimental setup. Consequently, a reasonable level of discrepancy between simulation and experimental results is expected. Irrespective of differences between the simulated and experimental setups, all the setups in simulation model with three different ATD models were identical. It is then still possible to observe the differences in ATD responses for the setup selected.

Although the input loading to the seating system through the carriage table has a pulse duration of merely 6 ms, the actual impact to the occupant's buttocks lasts more than 100 ms. Consequently, it was expected that the ATD responses would be different from those from the drop test discussed above. Figures 8-10 illustrate the pelvis acceleration, the DRI, and the lumbar force for the blast off test respectively. It was observed that ATD Model I, although the worst performer in the drop test, performed the best in the blast off test, with the values of pelvis acceleration, DRI, and lumbar force being closer to the experimental case.

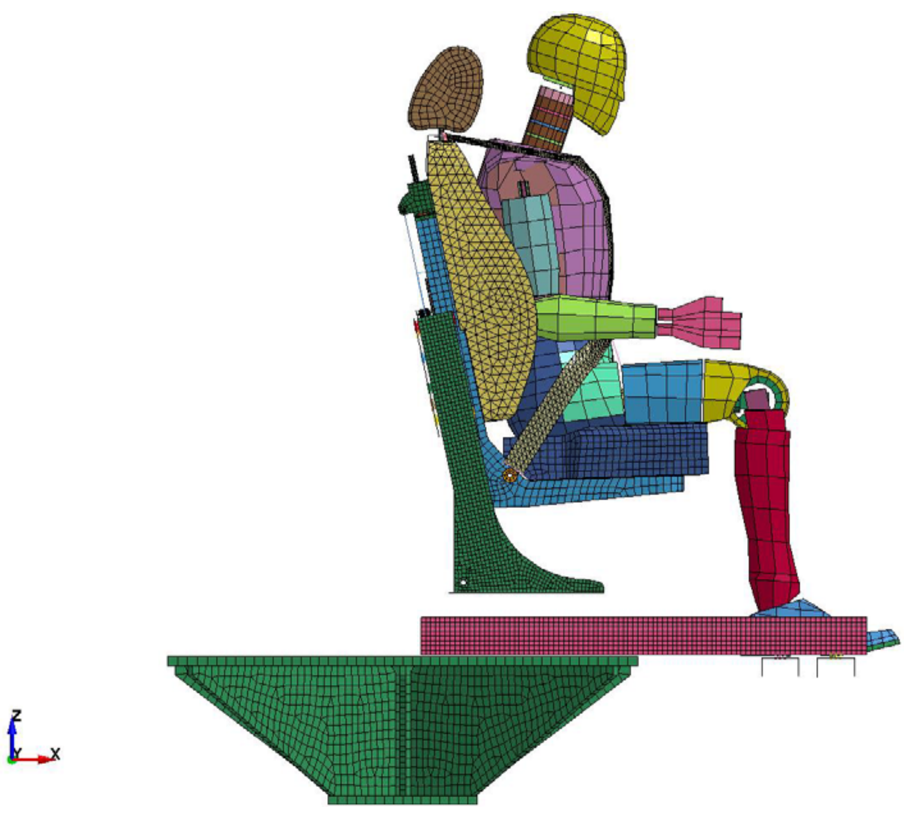

Figure 7: Numerical model of a seating system with ATD I

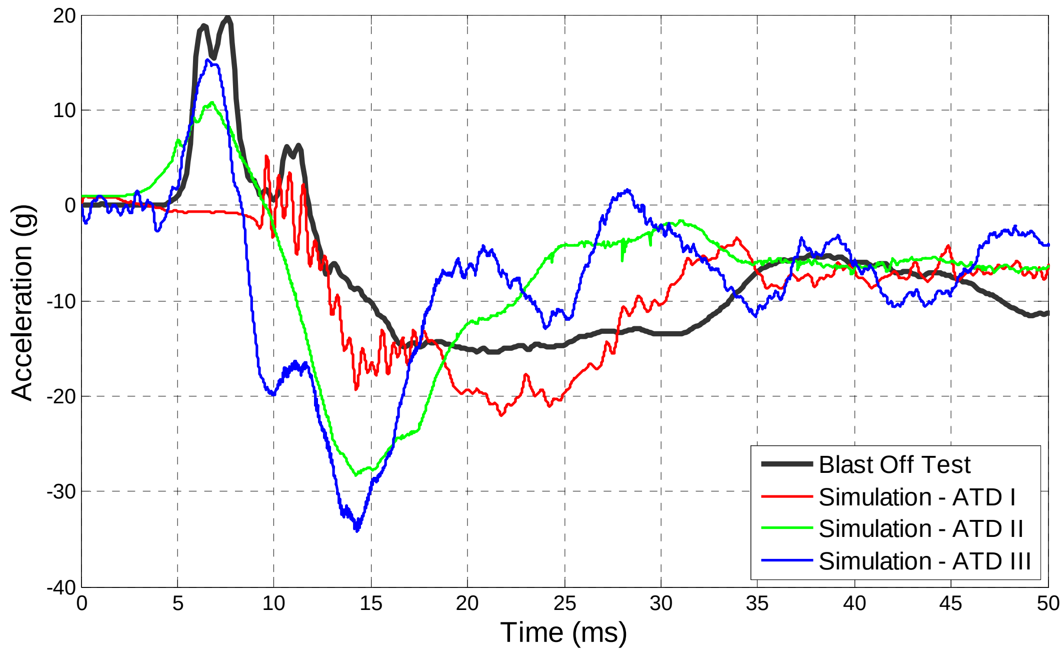

Figure 8: Pelvis acceleration histories in a blast off test

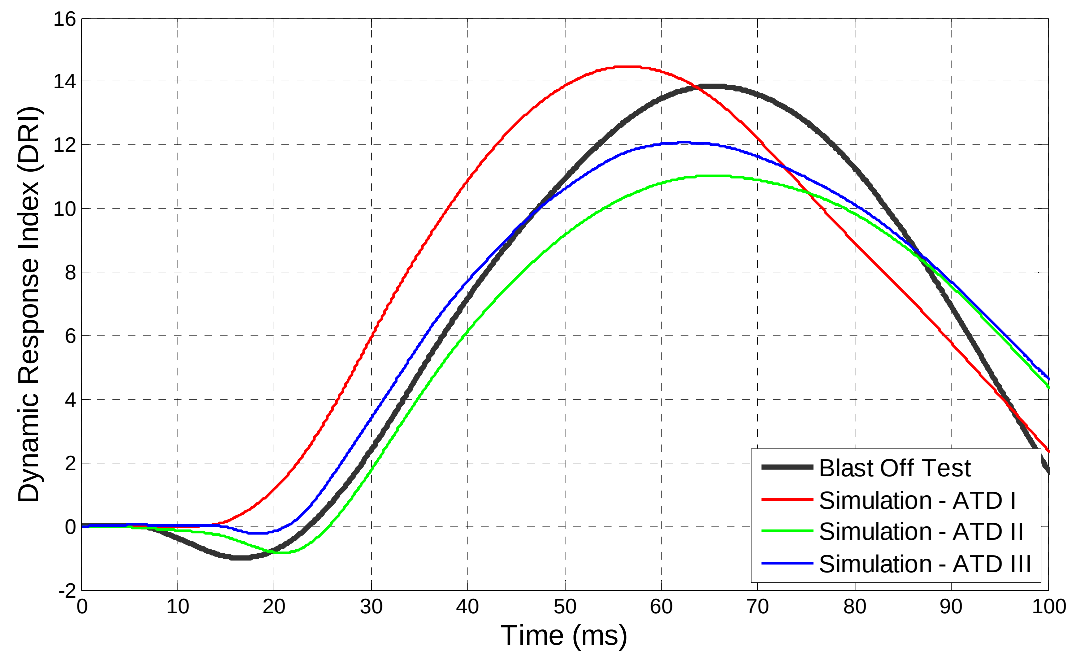

Figure 9: DRIs in a blast off test

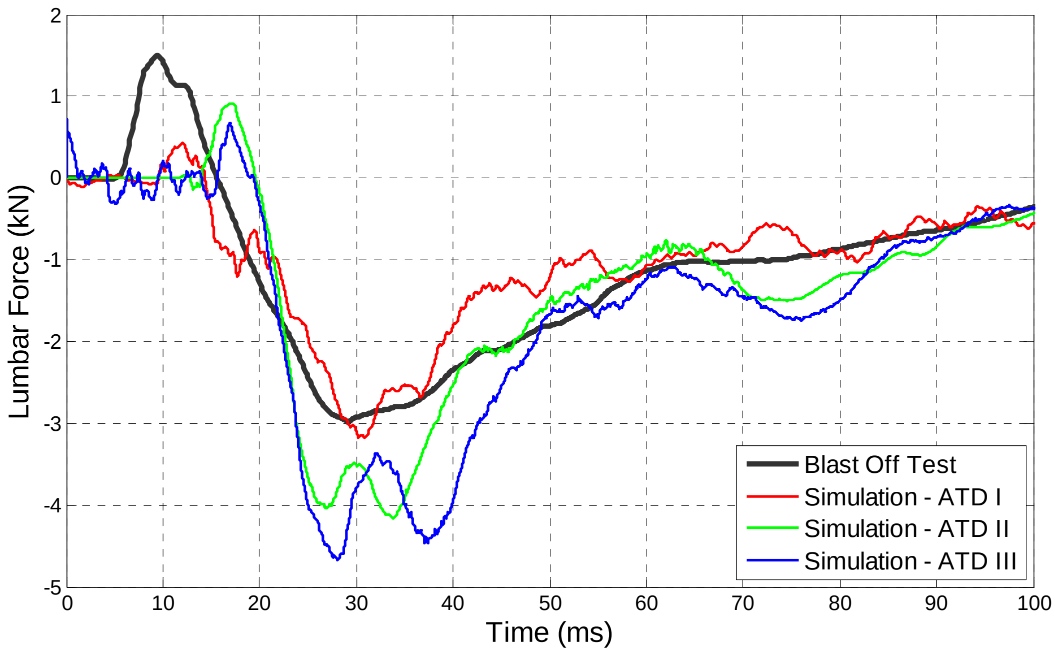

Figure 10: Lumbar force histories in a blast off test

Conclusions

A well planned test using a standard drop-tower facility to generate an impact pulse on the buttocks of a Hybrid III 50th percentile male ATD was conducted. Numerical models were then developed to simulate this test using three different numerical ATD models. It was found that none of the numerical ATD models investigated could generate accurate enough responses in terms of pelvis acceleration and axial lumbar force, when compared to the experimental drop test with the physical ATD model.

In order to further evaluate the validity of these ATD models, more complex simulations involving a blast mitigation seat in a blast off scenario were also performed and compared with actual experimental results. Similar observations were made in terms of deviations between numerical and experimental results. However, it was noted that the three ATD models behaved quite differently under this different impact loading (blast off) characterized by different loading characteristics. More specifically, the ATD model that exhibited the poorest comparison with the experimental drop-tower model, was found to perform the best under the blast off condition. This result suggests that some ATD models might be more suitable for specific impact conditions.

It is thus concluded that further enhancements to the three numerical ATD models are required for appropriately simulating military vehicle occupant responses under vertical loading for thoraco-lumbar spine injury assessment.

References

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3. AEP-55, Volume 2 (Edition 1), 2006. Procedures for evaluating the protection level of logistic and light armoured vehicles.